THE NONLINEAR EFFECTS IN 2DEG CONDUCTIVITY INVESTIGATION BY AN ACOUSTIC METHOD.

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Abstract

The parameters of two-dimensional electron gas (2DEG) in a GaAs/AlGaAs heterostructure were determined by an acoustical (contactless) method in the delocalized electrons region ($B \leq$2.5T).

Nonlinear effects in Surface Acoustic Wave (SAW) absorption by 2DEG are determined by the electron heating in the electric field of SAW, which may be described in terms of electron temperature T_e. The energy relaxation time τ_ϵ is determined by the scattering at piezoelectric potential of acoustic phonons with strong screening. At different SAW frequencies the heating depends on the relationship between $\omega\tau_\epsilon$ and 1 and is determined either by the instantaneously changing wave field ($\omega\tau_\epsilon< 1$), or by the average wave power ($\omega\tau_\epsilon> 1$).

72.50, 73.40.

Acoustical method employs a SAW propagating on a surface of piezoelectric substrate [1,2] (in our case $LiNbO_3$), which is accompanied by an electric field with frequency $\omega = 2\pi f$ equal to that of SAW, penetrating in the 2DEG channel, separated from the surface of a substrate by a vacuum gap a. In experiments we measure the absorption of SAW by 2DEG. Since the SAW absorption coefficient Γ is determined by the conductivity of 2DEG, quantizing of the electron spectrum in the magnetic field should result in peculiarities in absorption of SAW.

We studied the magnetic field B dependence of Γ in GaAs/AlGaAs heterostructures in B up to 2.5T in f range 30-210MHz at T=1.4-4.2K in the linear regime (input power $< 10^{-7}W$) and at T=1.5K for different SAW intensities. From previous studies [3] on the same samples we obtain the carrier density $n = 6.7 \cdot 10^{11} cm^{-2}$ and the mobility $\mu = 1.28 \cdot 10^5 cm^2/Vs$ at T=4.2 K (DC-data).

Curve 1 on figure 1 illustrates the Γ dependences on the magnetic field B at $T = 4.2K$. The maxima of Γ, as and minima of resistivity in a case of direct current measurements, are equidistant in inverse magnetic field. That allows one to find the carrier density, by the standard method, which yields $n = 7 \cdot 10^{11} cm^{-2}$. From $\Gamma(B)$, $\sigma_{xx}(B)$ was determined using the formula for $\Gamma(\sigma_{xx})$ of [4], and using a value of a obtained in a way presented in [3,5].

It was shown in [3] that at $B < 2.5T$, σ_{XX}^{AC} derived from the direct current measurements and σ_{XX}^{DC} derived from SAW absorption are equal, and we beleive electrons to be delocalized there. In this case one can determine another parameters of the 2DEG in the heterostructure.

Curve 2 of figure 1 presents the dependence σ_{xx} on B derived from dependence of $\Gamma(B)$.

In accordance with the Ando theory [6] $\sigma_{xx} = \sigma_{xx}^* + \sigma_{xx}^{osc}$, where $\sigma_{xx}^* = \sigma_0/(1+\omega_c^2\tau_p^2)$ is the classical Drude conductivity, τ_p is the transport lifetime, $\omega_c = eB/m^*c$ is the cyclotron frequency, m^* is the effective mass, and σ_0 is the zero-field conductivity. The oscillatory term is [6,7]:

$$\sigma_{xx}^{osc} \propto \sigma_{xx}^* D(X_T) exp(-\pi/\omega_c\tau_q) cos(2\pi E_F/\hbar\omega_c - \pi) = \Delta\sigma_{xx} cos(2\pi E_F/\hbar\omega_c - \pi)/2, \quad (1)$$

where $D(X_T) = X_T/sinh(X_T)$, $X_T = 2\pi^2 T/\hbar\omega_c$, is determined by the temperature broadening of the Fermi level, E_F is the Fermi energy, τ_q is the quantum lifetime, which is a measure of the collisonal broadening of the Landau levels at the value of $A = \hbar/2\tau_q$, and $\Delta\sigma_{xx}$ is the oscillation amplitude.

From the slope of $\sigma_{xx}^*(1/B^2)$ one obtaines μ_0 at $B = 0$. The mobility μ_0 appeared to be equal to $(1.1 \pm 0.1)10^5 cm^2/V \cdot s$ (15 percent difference from the Hall mobility) and does not depend on temperature.

From the analysis of the maximal amplitude $\Delta\sigma_{xx}$ value (fig.1) one can get the classical-to-quantum scattering time ratio τ_p/τ_q, which is equal to 5.5$\pm$0.5 and corresponds to a case of dominance of screened-Coulomb scattering of electrons from ionized charge centers [8]. The Dingle temperature is $T^* = \hbar/2\pi\tau_q = 1.5K$. In accordance with [9] using the known ratio τ_p/τ_q and the carrier sheet density one can estimate the spacer thickness, which takes a value of $\sim 30\mathring{A}$.

Let's consider the nonlinear effects at relatively low B. The dependences of Γ on T and SAW intensity were obtained from the experimental curves of the type presented in Fig.1. Fig.2a illustrates the temperature dependence of $\Delta\Gamma = \Gamma_{MAX} - \Gamma_{MIN}$, where Γ_{MAX} and Γ_{MIN} are the values of an adjacent minimum and maximum of Γ, measured in a linear regime at a frequency of 150 MHz. Fig.2b presents the $\Delta\Gamma$ dependence on the output power P of the RF source of SAW at 150 MHz at T=1.5 K. It is seen, that $\Delta\Gamma$ decreases with the P and T increase.

It's quite natural to consider the nonlinearity mechanism, which was investigated earlier on these structures using direct current [10], where it has been shown that the dependence of the resistivity on the current density can be explained by the 2DEG heating.

For a description of the electron gas heating using temperature T_e, which differs from the lattice temperature T_0, the condition $\tau_p << \tau_{ee} << \tau_\epsilon$ is to be met (τ_{ee}, τ_ϵ are the electron-electron collision time and energy relaxaton time respectively). τ_p can be derived from the value of μ_0 and is equal to $\tau_p = 5 \cdot 10^{-12}s$. In [11] we obtained $\tau_{ee} = 5 \cdot 10^{-10}s$, $\tau_\epsilon \simeq 3.3 \cdot 10^{-9}s$.

By analogy with [10] one can determine T_e- the temperature of 2DEG- comparing the dependence of $\Delta\Gamma$ on P with its temperature dependence .

In order to find the energy losses Q, we have made the following calculations: the electric field E, corresponding to a SAW propagating in a piezoelectric, and penetrating in a 2D system, is:

$$|E|^2 = K^2 \frac{32\pi}{\nu}(\epsilon_1 + \epsilon_0) b \frac{kexp(-2ka)}{1 + [(4\pi\sigma_{xx}/\epsilon_s v)c(k)]^2} W, \tag{2}$$

where K^2 is the electromechanical coupling coefficient, v, k are the SAW velocity and the wave vector; ϵ_0 , ϵ_1 , ϵ_s are the dielectric constants of vacuum, the piezoelectric and the sample respectively, W is the input SAW power in the sample per sound track width. The functions b and c are complex functions of ϵ_0, ϵ_1, ϵ_s, k, a. The energy losses per one electron $Q = e\mu E^2$. Multiplying the both parts of Eq.(2) by σ_{xx}, one obtains $Q = 4W\Gamma/n$.

We have invesigated the dependencies $Q = f(T_e^3 - T_0^3)$, which in accordance with the results of [10] obtained for a DC, should correspond to the energy relaxation of electrons on piezoelectric potential of acoustic phonons (PA-scattering) in case of weak screening [12]. However, we find that our experimental curves can be fitted better by $Q = A_5(T_e^5 - T_0^5)$ which corresponds to the case of PA-scattering with strong screening [12]. This is also in better accordance with our experimental situation, because the strong screening condition is fulfilled for the studied sample. Figure 3 shows the experimental points and theoretical dependencies $Q(T_e^5 - T_0^5)$ for f=30 and 150 MHz with $A_5 = 3 \pm 0.5 eV/sK^5$ and $4.1 \pm 0.6 eV/sK^5$, respectively.

Besides, it should be noticed that A_5 takes different values for different frequencies. This difference is associated probably due to the fact that in the case of 150MHz $\omega\tau_\epsilon > 1$ the heating is determined by average wave power, whereas at f=30MHz and $\omega\tau_\epsilon < 1$ the 2DEG heating is determined by the instantaneously changing wave field. That can lead to the different heating degree for the same energy losses.

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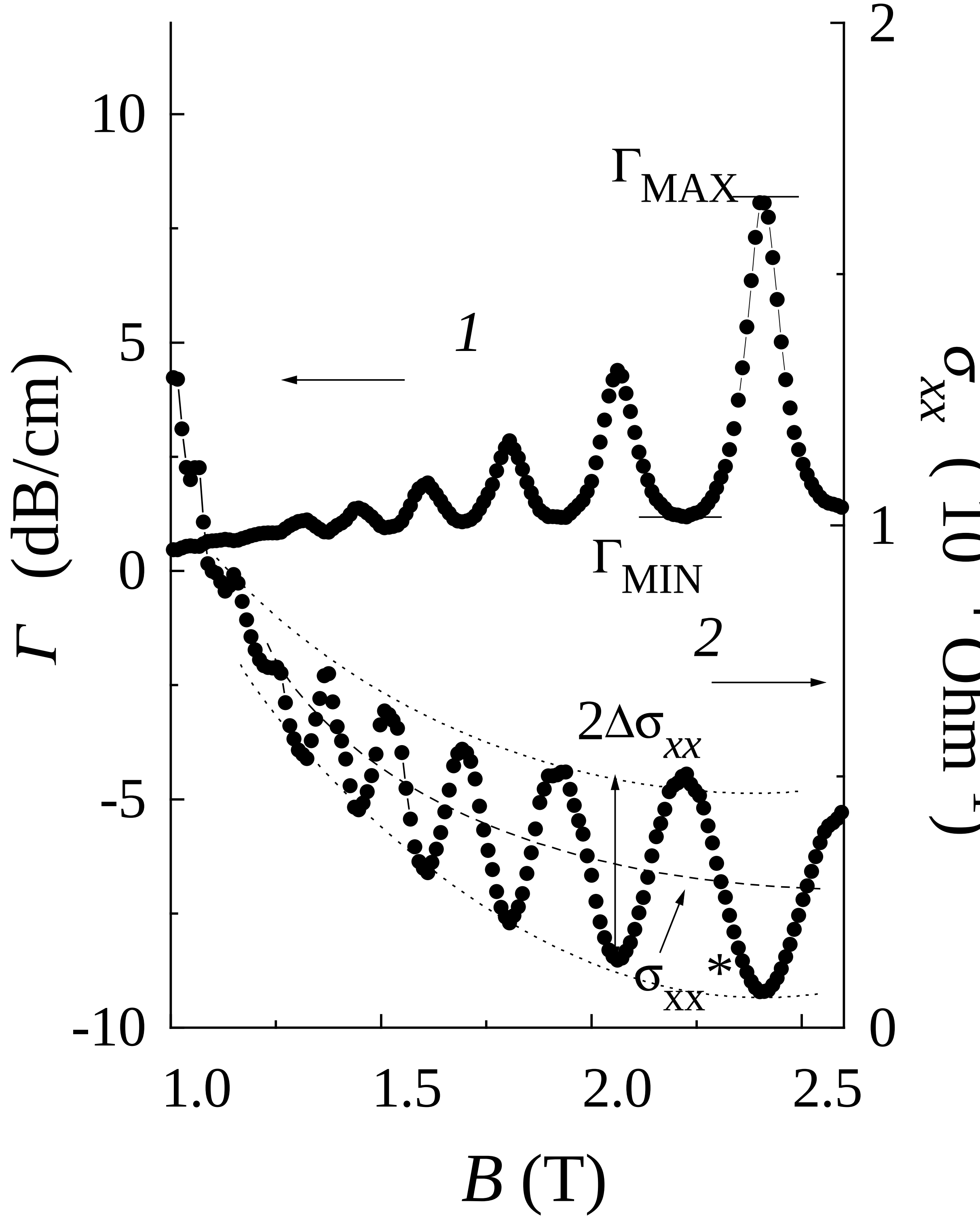
FIGURES

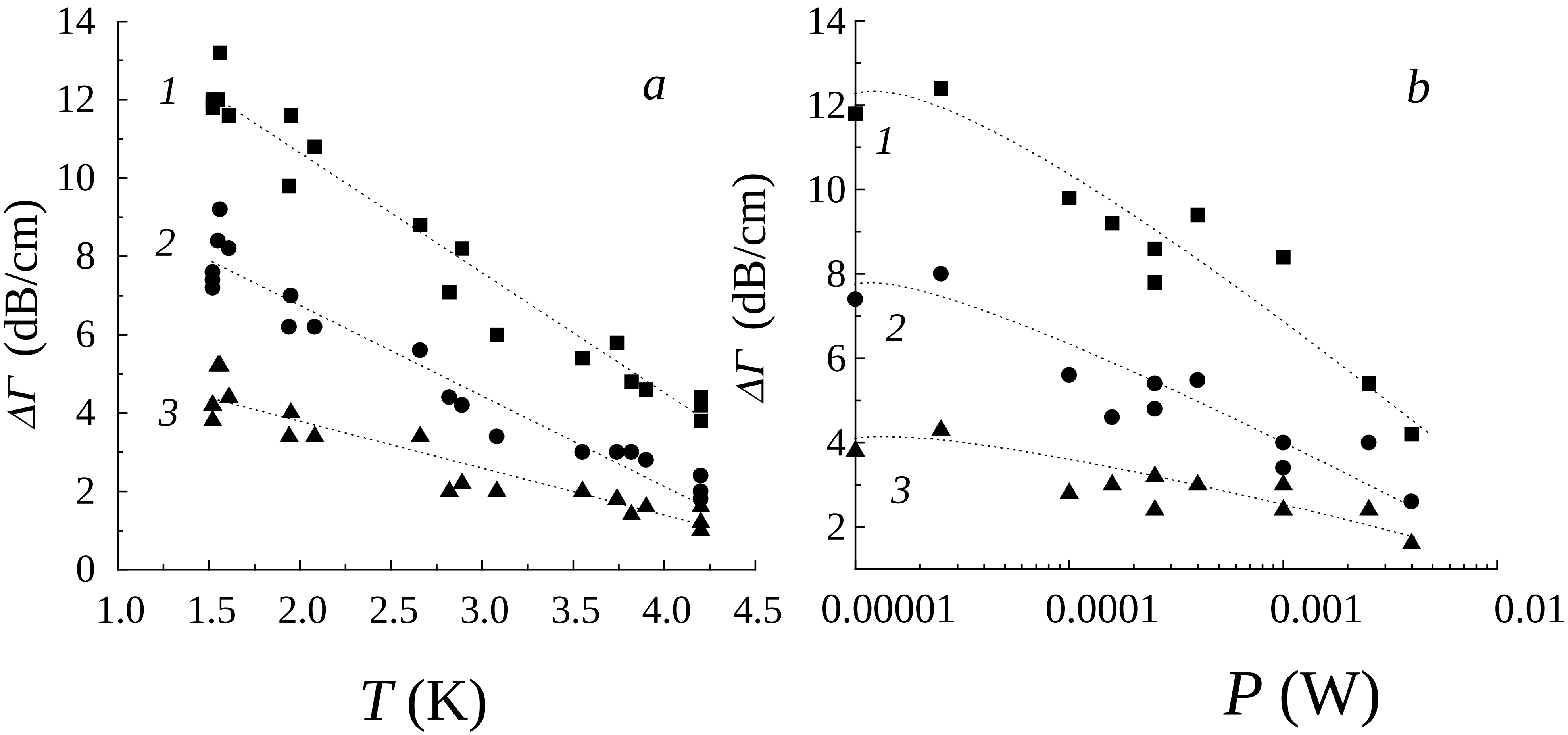
FIG. 1. The experimental dependences of the absorption coefficient Γ (1) and of the 2DEG conductivity $\sigma_{xx}(2)$ on magnetic field at $T = 4.2K$ at frequency 30MHz.

FIG. 2. The $\Delta\Gamma$ dependence on temperature (a) and on power (b) at 150MHz for different magnetic fields B: 1-1.75T, 2-1.5T, 3-1.41T.

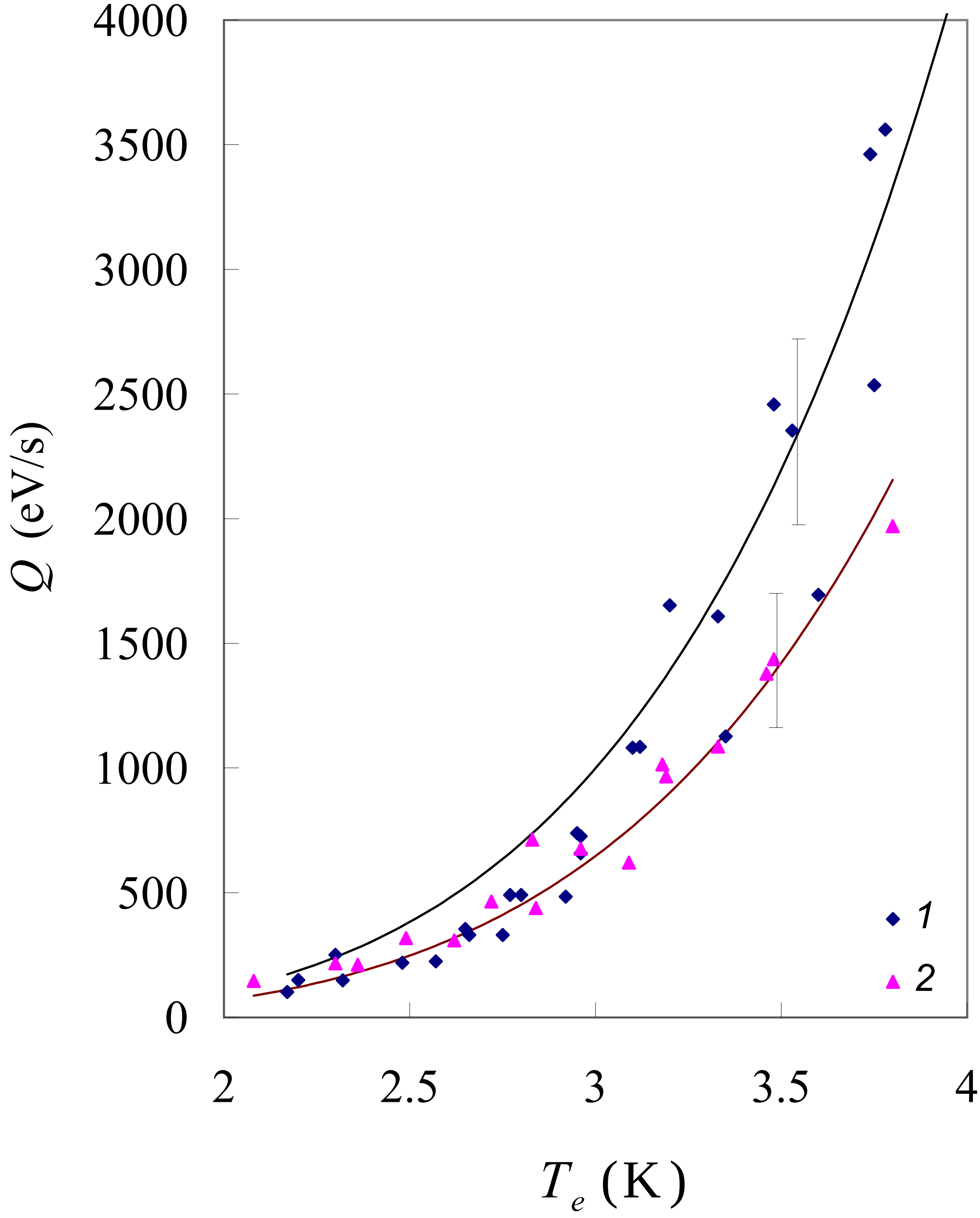
FIG. 3. The dependence of the energy losses Q on the temperature T_e for two frequencies (1-150MHz, 2-30MHz).



10
5
0
-5
-10
2
1
0
1.0
1.5
2.0
2.5
B (T)
Γ (dB/cm)
σxx (10^-4 Ohm^-1)
1
2
ΓMAX
ΓMIN
2Δσxx
σxx*



14
12
10
8
6
4
2
0
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
ΔΓ (dB/cm)
T (K)
a
1
2
3
0.00001
0.0001
0.001
0.01
P (W)
b



4000
3500
3000
2500
2000
1500
1000
500
0
Q (eV/s)
2
2.5
3
3.5
4
T_e (K)
1
2